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TEMPERATURE MONITORING

OF AN

INSULATED WATERMAIN



Pollution Control Branch
Ontario Ministry of the Environment

October, 1976

RP 2044

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TEMPERATURE MONITORING OF AN INSULATED WATERMAIN

1.0 INTRODUCTION

The land mass of the Province of Ontario extends from approximately 42° N. Lat. on the south to approximately 55° N Lat. in the north. The populated and urbanized area is generally south of 51° N Lat. and is not within the region of permafrost. The area north of approximately $45^{\circ} 30'$ N. Lat. is, however, subjected to relatively wide variations in temperatures (30°C summer to -40°C winter) and to essentially continuous below-freezing temperatures for five months of the year. Consideration must therefore be given to frost protection for sewers and watermains in any design for this region.

A further factor is the geological character of the region. The area lies within the Precambrian Shield and was subjected to pleistocene glaciation (Patrician Centre), resulting in massive granite outcroppings and generally shallow soil depths. Obtaining adequate depths of soil for burial of sewers and watermains is thus difficult at best, and generally the installation of such services involves rock excavation.

The use of artificial insulation to provide frost protection for buried pipelines, without the extensive (and expensive) excavation required to obtain soil cover, is an apparent solution.

This paper provides the results of an investigation carried out on an insulated, shallow-buried watermain.

2.0 EXPERIMENTAL INSTALLATION

2.1 General

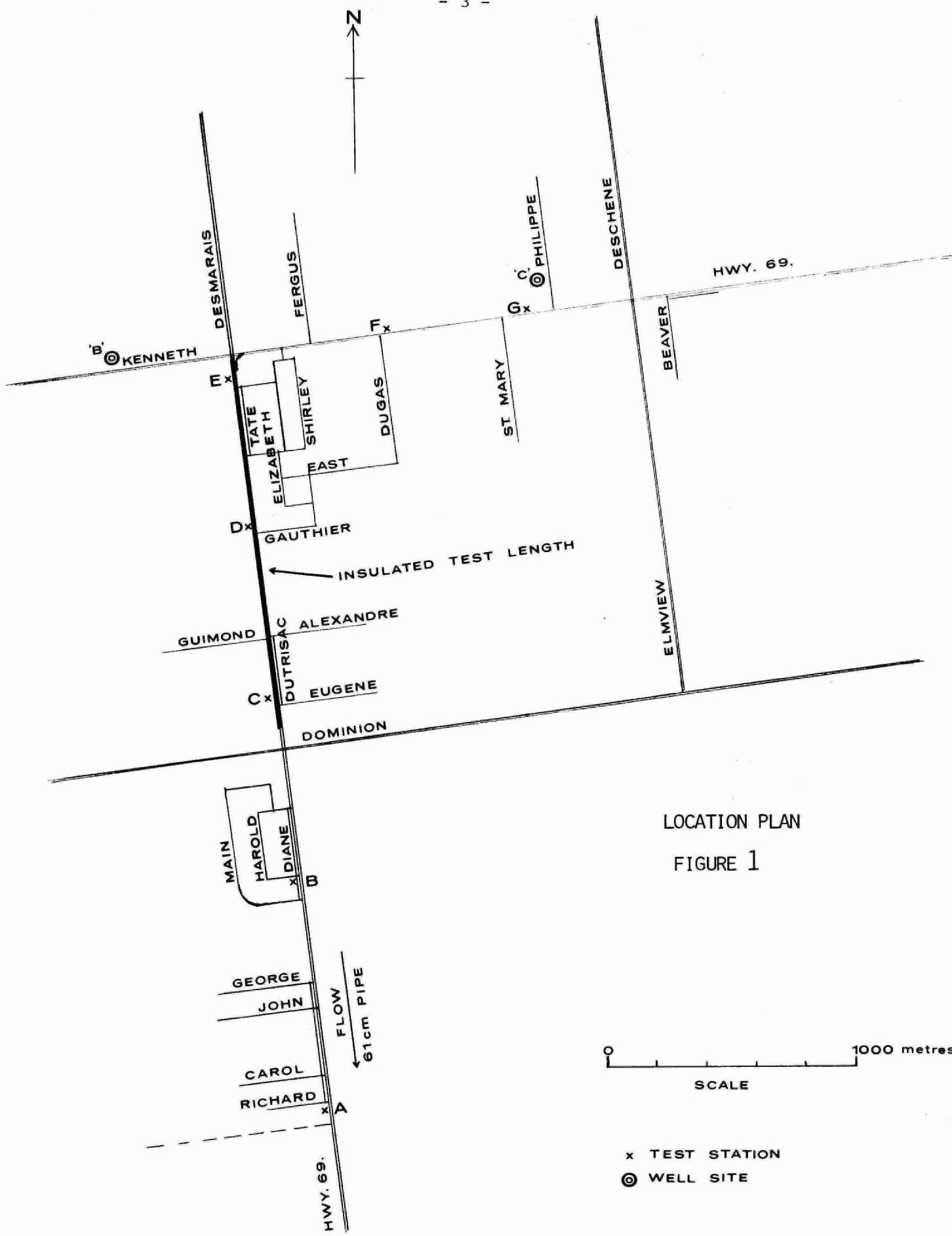
In 1972 the Ontario Ministry of the Environment, as part of its capital works program, contracted for the design and construction of approximately 24 miles (39 km) of 24-inch diameter (61 cm), reinforced-concrete watermain to provide a water supply for the Town of Chelmsford (app. Lat. $46^{\circ} 35' N$; Long $81^{\circ} W$).

The pipe was to be buried generally to a depth of 5'-6" (1.7 m) minimum cover but a decision was made to install approximately 5000 feet (1.5 km) at a minimum depth of 3'-6" (1.1 m), insulated with an over-lying 2" (5 cm) thick by 8 ft (2.4 m) wide slab of expanded polystyrene ("Styrofoam") as a test section. Temperature monitoring was provided for this section, as well as for adjacent "normal" sections.

2.2 Construction and Equipment

Figure 1 shows the location of the watermain and test section; Figure 2 shows typical cross-sections in the normal and test-sections, as well as the location of temperature monitoring probes.

Seven temperature monitoring stations were installed, three of which were in the insulated section; two stations were automatically recorded with the others having provision for manual readout. Each station consisted of six thermistors located in and around the pipe as shown in Figure 2 with all leads carried through a vertical piece of $2\frac{1}{2}$ " diameter (6 cm) PVC pipe to a surface junction box. The automatic stations each had three, 2 track, strip-chart recorders contained in a heated and insulated, pole-mounted box. Charts were adequate for 30 days operation. Manual read-out stations were checked once each week.

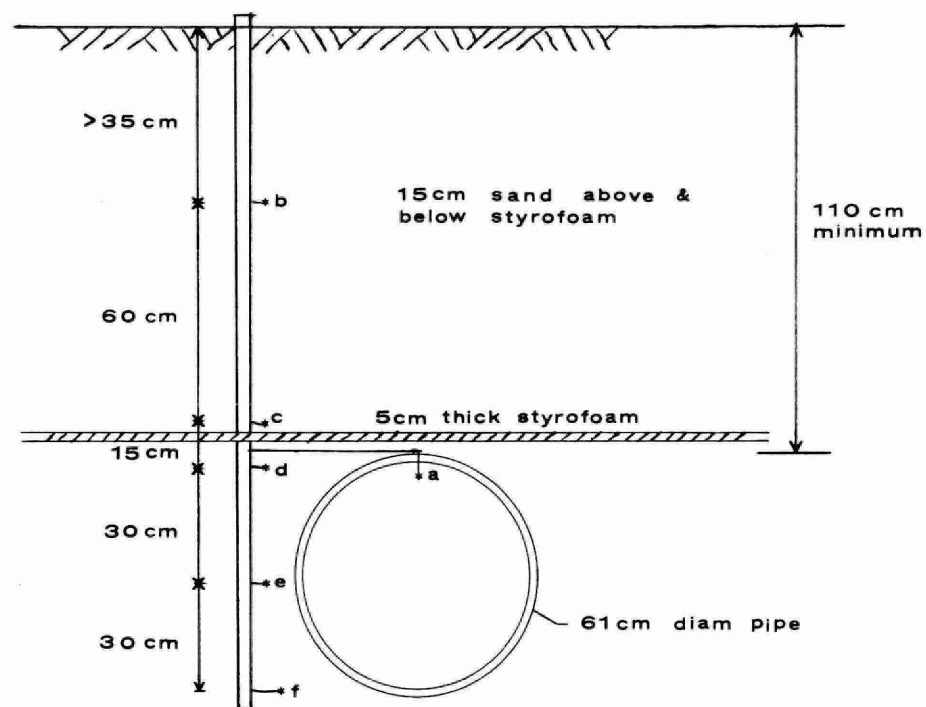
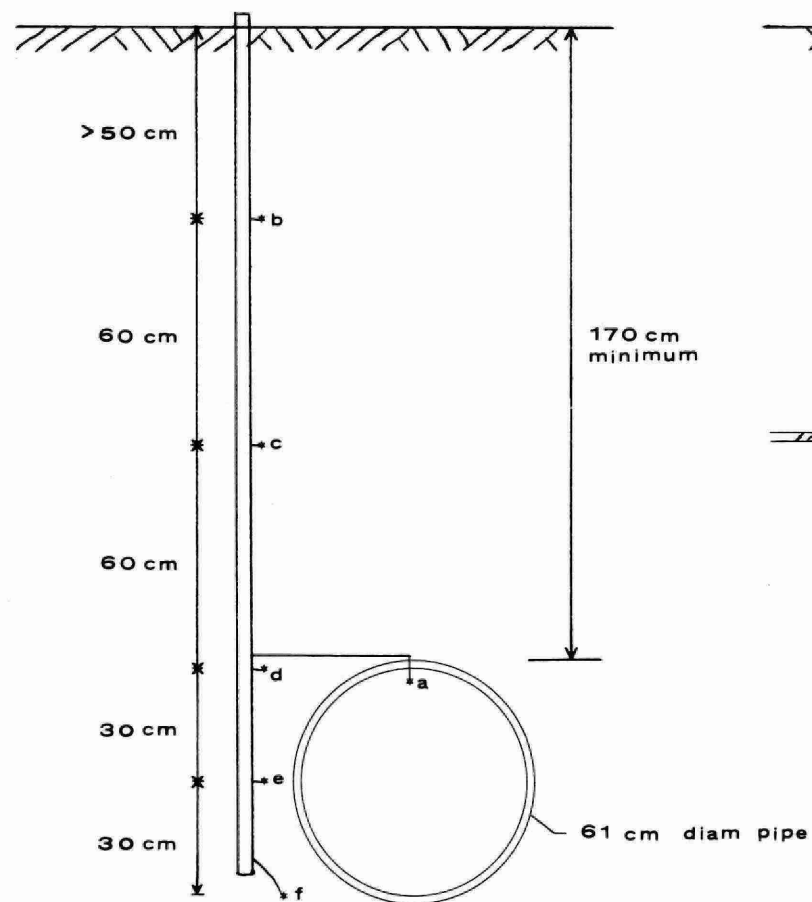
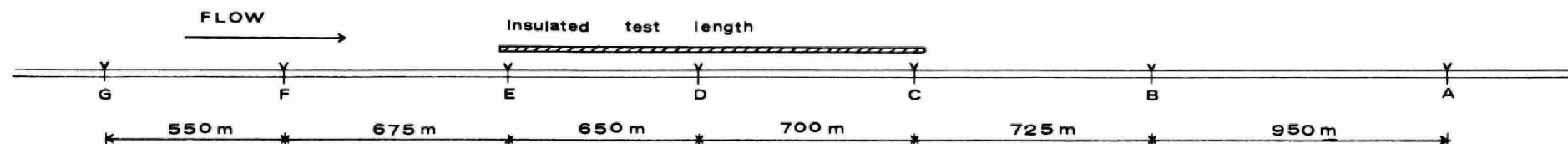


LOCATION PLAN

FIGURE 1

0 1000 metres
SCALE

x TEST STATION
© WELL SITE



TYPICAL CROSS-SECTION

FIGURE 2

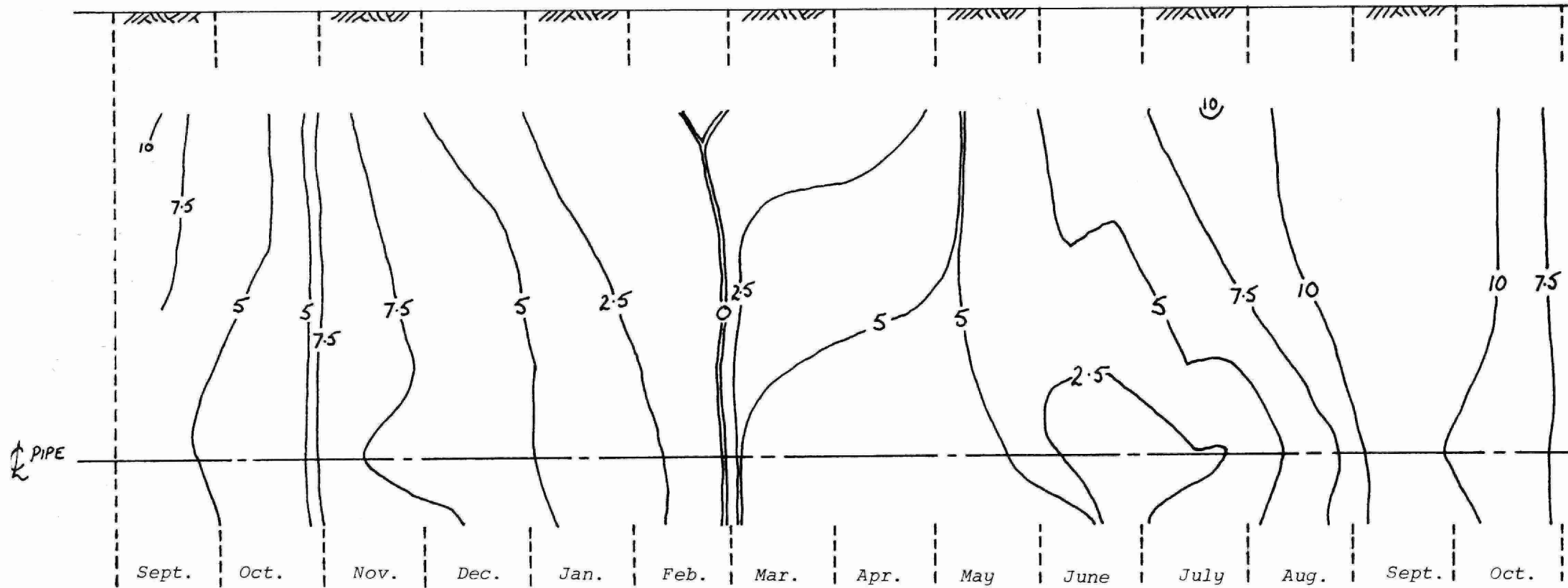
3.0 RESULTS

The system was monitored over a period of sixteen months. The soil temperature profile is shown for the uninsulated section in Figure 3A, for the insulated section in Figure 3B.

Figure 4 shows the relationship of the average air temperature, soil temperature adjacent to the pipe and the temperature of the water in the pipe.

Table I shows mean monthly temperature of water, air and soil at selected stations representative of the uninsulated and insulated sections, arranged in direction of flow. Well water was introduced into the system upstream of "G" and again upstream of "E" (See Figure 1).

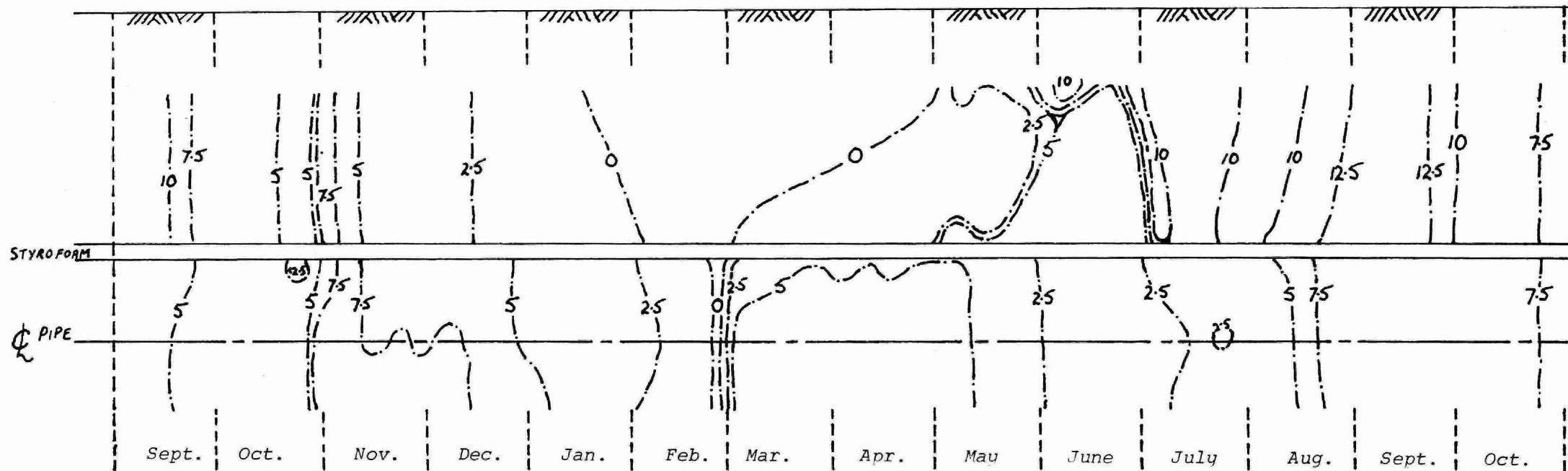
WATERMAIN



SOIL ISOTHERMS

FIGURE 3A

WATERMAIN - STYROFOAM INSULATED



SOIL ISOTHERMS

FIGURE 3B

TEMPERATURE PROFILE

FIGURE 4

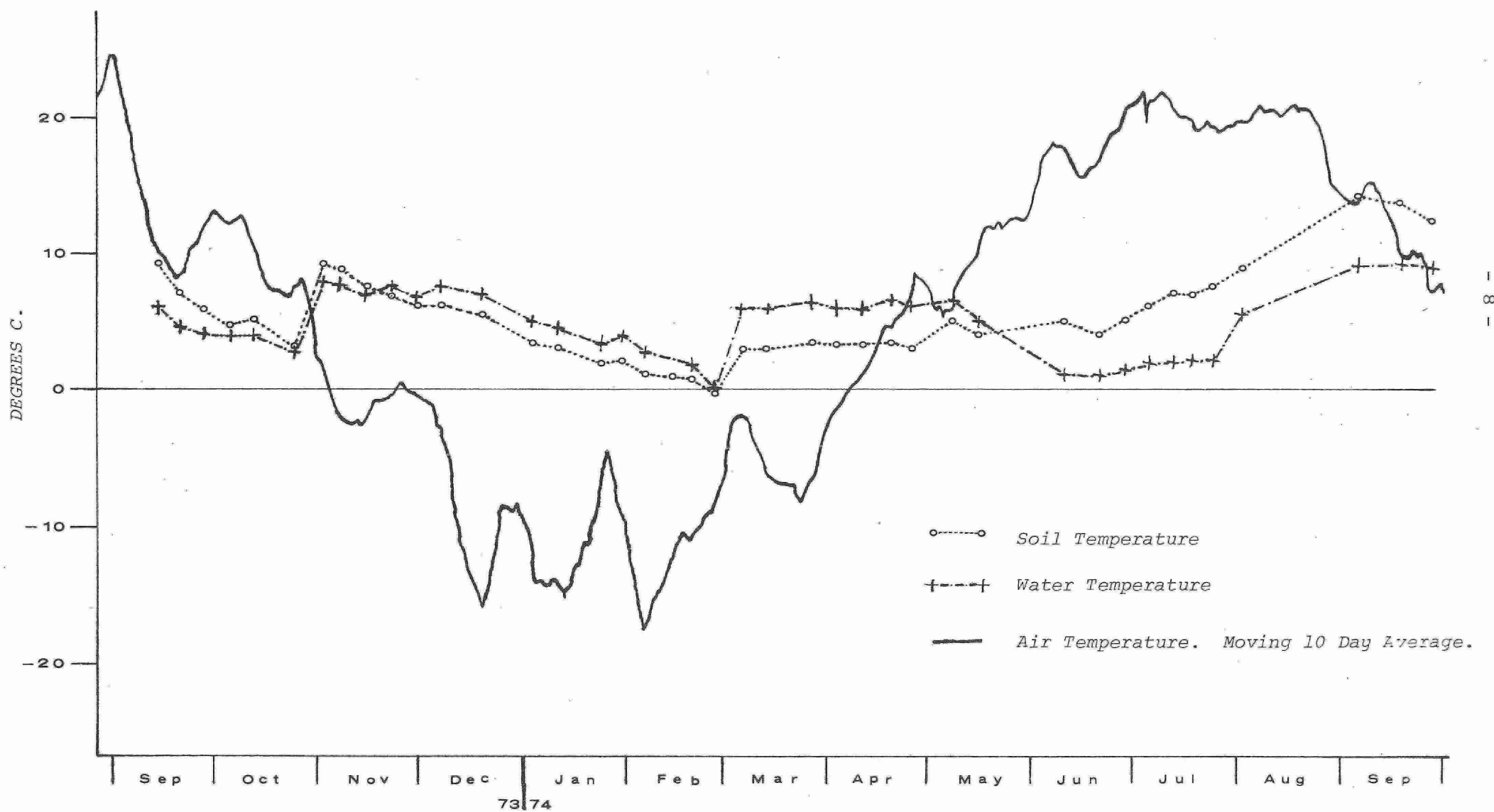


TABLE I

Mean Monthly Temperature - °C

	Water				Air	Soil
	G*1224m	→ B*1350m	→ C*1675m	→ A	(mid-day)	at 1 m
Sept./73	4.5	4.5	4.8	5.0	9.5	7.4
Oct.	3.5	3.3	3.2	3.0	6.8	4.1
Nov.	7.2	7.4	7.5	7.4	4.4	4.9
Dec./73	7.5	7.0	7.4	7.3	-10.0	3.5
Jan./74	5.7	4.5	4.0	4.2	- 2.0	1.8
Feb.	3.2	2.0	1.8	1.6	- 3.7	0.4
Mar.	6.5	6.8	7.6	6.2	6.4	1.8
Apr.	6.2	7.2	6.2	6.1	12.8	2.0
May	6.0	7.0	5.3	5.7	12.5	6.0
June	8.4	8.8	7.0	-	18.6	10.3
July	-		probe failure		-	-
Aug.	-	-	-	-	-	-
Sept.	8.3	8.4	7.8	9.1	20	12.0
Oct.	7.9	7.6	7.8	8.1	7.2	8.3
Nov.	5.1	5.2	5.2	5.4	3.0	4.6
Dec./74	7.1	8.3	7.6	7.9	2.7	4.0
Period	—	—	—	—		
Mean	6.26	6.29	5.94	5.92		
Nov. to						
Mar. Mean	6.02	5.54	5.66	5.34		

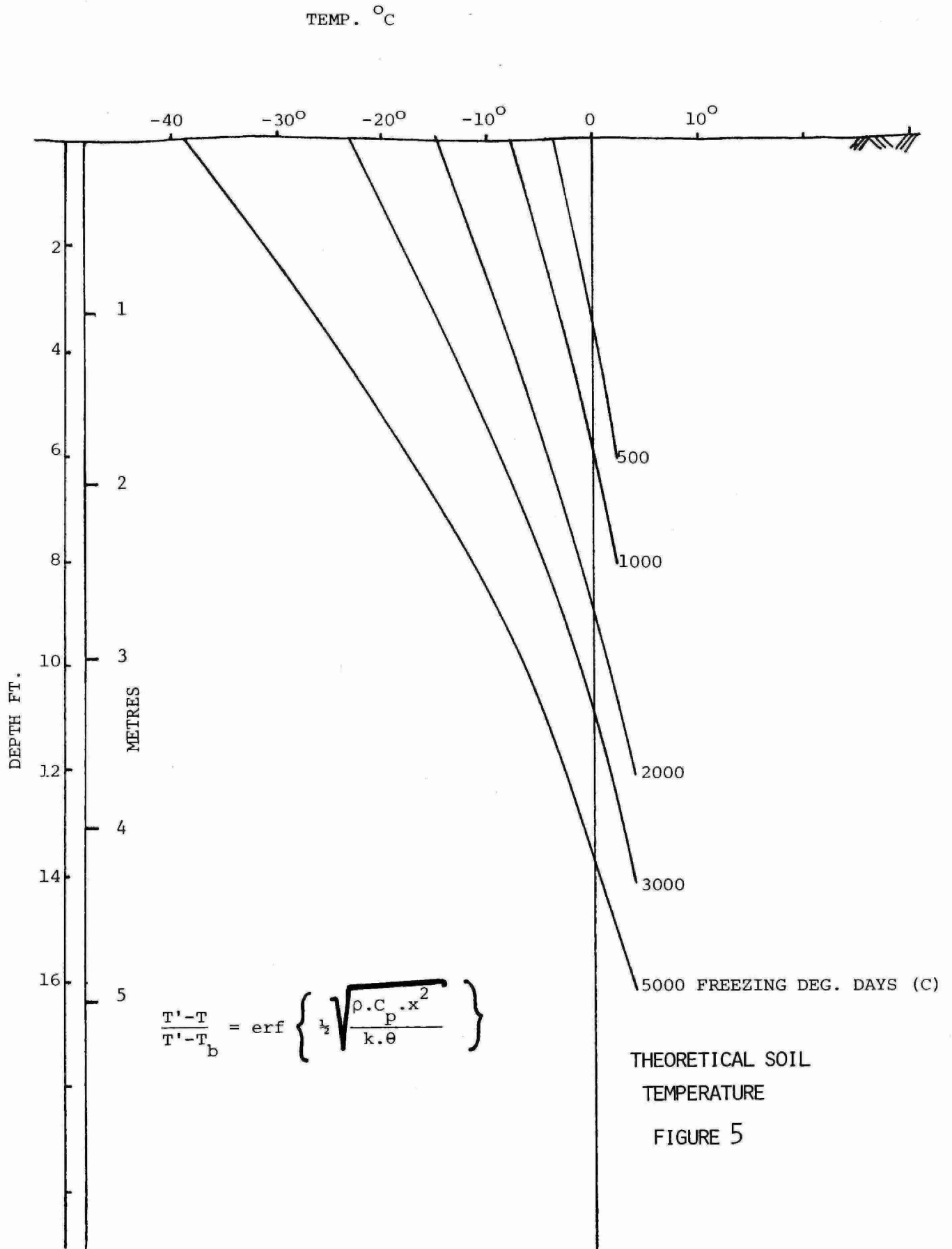
4.0 DISCUSSION

4.1 Soil Temperature Profiles (Figs. 3A and 3B)

An examination of Figures 3A and 3B indicates that the insertion of a layer of styrofoam did not prevent the penetration of freezing temperatures into the soil to the depth of the pipe centre line, but neither did a 1.7 m soil cover. Thus, in this respect the insulation could be said to provide a condition equivalent to that obtained by an additional two feet of soil cover. However, an examination of Figure 3A shows that no temperature which was obtained at a depth of 1.1 m was not obtained at a depth of 1.7 m and therefore the additional two feet of cover would not provide significant additional protection against frost penetration.

A theoretical analysis of annual minimum soil temperatures for the location of this work (app. 1500 Freezing-Degree Days annually) indicates that 0°C temperatures would be obtained at a depth of 2.3 m (7.6 ft); the minimum temperature at 1.1 and 1.7 m would be -6° and -3° respectively. (See Figure 5). The worst condition prevailed for such a short period of this study that it has not been possible to confirm (or dispute) these theoretical values; the deepest temperature probe was at 2.28 m and therefore confirmation of the depth of maximum frost penetration is also not available.

An examination of Figure 3B shows an effect which can be attributed to the presence of the insulation; the block of soil above the insulating layer cooled more quickly and remained cold longer than the equivalent soil in an uninsulated area. The insulation thus had a notable retarding effect on heat transfer from the relatively warm soil at depth to the surface soil with the onset of colder surface



temperatures. There is no significant delay in the occurrence of cold temperatures below the insulation layer as compared to uninsulated sections and it is hypothesized that as the soil outside and below the area covered by insulation cooled, the soil under the insulation lost heat laterally through a horizontal soil column one-half the width (i.e. app. 1m) of the insulation above. It thus appears that for flat-slab insulation to have a significant effect on soil temperatures surrounding a pipe, the slab would of necessity be equal, in centre-line to outside dimension, to the height of soil column required if insulation were not used.

On this basis, if a design were required to provide complete protection against freezing temperatures, an equivalent soil depth of 2.3 m would be required and could be obtained by a slab of Styrofoam 4.6 m wide (2 x equivalent soil depth) and of a thickness such that the depth of soil plus twelve (the ratio of heat transfer coefficients of soil and Styrofoam) times the thickness of insulation equals 2.3 m.

e.g.: required equivalent soil depth = 2.3 m

required insulation width = $2 \times 2.3 = 4.6$ m

" " thickness: $D_{\text{soil}} + (12 \times D_{\text{ins}}) = 2.3$ m

for 1 m soil cover

$$D_{\text{ins}} = (2.3 - 1)/12 = 0.11 \text{ m}$$

4.2 Air, Soil, Water Temperature Relationship:

Figure 4 shows the variation with time of the temperatures of air, the soil adjacent to a buried pipe and the water within the pipe. It is apparent from Figure 4 that the temperature of water in a

pipe and the temperature of the surrounding soil tend to coincide and react relatively quickly to a change in either one. The soil temperature is a function of the ambient air temperature but due to the insulating effect of the soil overlying the monitored point, there is a lag in response. The soil temperature tends to follow air temperature but may continue a trend after a similar trend has been reversed in the air temperature. The use of effective flat-slab insulation may, it is postulated, accentuate this lag effect and although the onset of freezing conditions may be delayed, the duration of such conditions, once established, could be prolonged. It is thus considered necessary to use a higher safety-factor (ie: greater equivalent soil depth) when designing insulated as opposed to uninsulated pipe lines.

4.3 Pipe Line Heat Losses:

The watermain under study had an intermittent flow which provided an average delivery of 0.8 mgd ($3600 \text{ m}^3/\text{day}$) and thus an average water velocity of 0.5 fps (0.15 m/s). The average liquid residence time in the monitored sections are thus 2.3 h for Section G-E, 2.5 h for Section E-C (insulated) and 3.1 h for Section C-A. The change in water temperature due to heat loss to, or gain from, the surrounding soil is very small under normal flow conditions and lies within the range of instrument error. It is thus difficult to determine with a high degree of confidence what changes, if any did occur. Table I does however indicate that differences between the insulated and uninsulated sections did exist.

By taking the mean water temperature at each station over the period of record it is indicated that the water maintained a relatively stable temperature in the uninsulated sections but, on an annual net basis, lost heat in the insulated section. This would indicate that the insulation prevented, to some degree, heat gain during periods of high ambient temperature. By examining the mean temperatures over the period from November to March inclusive there is indication of heat loss in the uninsulated sections and stable temperatures over the insulated section.

These indications of variation are in conformity with the theoretical performance of the system but it is cautioned that this variation is small and within the limits of possible error in the data (standard deviation of the data is approximately 2° ; variation is in the order of 0.5°) and therefore, while the data are not in conflict with theoretical performance, they do not provide conclusive evidence in support of such theory.

4.4 Consequences of Frost Penetration

The existence of freezing or below freezing temperatures in the soil surrounding a watermain can be detrimental in two ways; the contents of the pipe can freeze with consequent rupture of the pipe and disruption of service, and/or the movement of the soil and pipe bedding due to formation of ice lenses can induce mechanical stresses in the pipe with, again, possible rupture of the pipe and disruption of service.

The documentation of the latter effect is not within the scope of this study but at the time this report is being written

an experimental installation including strain gauges is being constructed and will provide such documentation. If it is necessary to eliminate frost penetration to the pipe bedding it can be done by providing adequate natural soil cover or by introducing insulation as discussed in Section 4.1.

The existence of freezing or below freezing temperatures in the soil surrounding a watermain does not necessarily result in freezing of the pipe contents. Before freezing can occur the heat of the water must be lost (4.19×10^3 J/kg/ $^{\circ}$ C) and then the heat of fusion (332×10^3 J/kg) must be dissipated. For the watermain considered in this study, one metre of pipe will, when full, contain approximately 290 kg of water. At an initial temperature of 6° C a loss of 7.3×10^6 J per metre of pipe must occur in order for the water temperature to be lowered to 0° C and a further loss of 96×10^6 J before the contents are totally frozen. The rate of heat loss may be calculated by basic heat transfer mathematics;

$$\frac{dQ}{d\theta} = -k.A. \frac{dt}{dx} \quad \text{(Fourier's Law)}$$

in which $\frac{dQ}{d\theta}$ = rate of heat flow

A = area at right angles to direction of heat flow.

$-\frac{dt}{dx}$ = temperature gradient

k = thermal conductivity of surrounding material

Note: for pipes use

$$A_{avg} = (A_2 - A_1) / \ln A_2 / A_1$$

The initial rate of heat loss will be at its maximum as the temperature gradient ($\frac{dt}{dx} = \Delta T$) is at its maximum, and the rate will decrease as the temperature of the pipe contents approaches the temperature of the surrounding soil. After the water temperature has reached 0°C the temperature gradient will remain essentially constant and the rate of heat loss will become constant.

Thus, given a design temperature for the soil surrounding a watermain, (see Figure 5) the theoretical "time to freeze" may be calculated and, knowing the length of watermain and flow velocity it may be determined if the contents may be frozen under operating conditions. This is not generally a limiting condition but rather the "no-flow" conditions which are critical. From the calculated time to freeze the maximum allowable shut-down time may be determined.

An analysis of the watermain under study indicates that, with a temperature of -5°C in the soil surrounding the pipe, and with the water initially at $+6^{\circ}\text{C}$, the water would cool to 0°C in approximately 11 hours and would freeze in a further 210 hours. Table II shows the minimum water temperatures recorded during this study (February 27/74) and these are consistent with the above analysis.

The theoretical time for a loss of 1°C at $\Delta T = -6^{\circ}$ is 9.6 hours; the "average" liquid residence time from station G to station A is 7.9 hours.

TABLE II

Minimum Recorded Water Temperatures -
February 27, 1974.

G	1.0°C
F	0.8
E	0.8
D	- (non-op.)
C	1.2
B	-
A	0

5.0 CONCLUSIONS

From data collected in this investigation, from inferences provided by those data and from theoretical analysis not refuted by the data, the following conclusions have been reached:

1. Freezing and below freezing temperatures occur in soil at depths greater than those recognized by "generally accepted practice".
2. Flat slab insulation as installed in this study, while producing measurable differences when compared to non-insulated sections, did not provide significant benefits in protecting the watermain against freezing.
3. Flat slab insulation can be designed and installed in a manner that will preclude the occurrence of freezing temperatures adjacent to an underlying watermain but if such an installation is constructed, consideration must be given to possible negative effects induced by the fact that such insulation will not only retard heat loss, but will also retard heat gain, in the soil.
4. If the critical condition is freezing of the pipe contents, rather than mechanical stresses caused by freezing of the pipe bedding, the best protection will be provided by ensuring that the pipe flow is such that the liquid residence time is less than the time to freeze.
5. Existing theory, and techniques for the application of such theory, are adequate for the design of watermains to be protected against freezing.

6.0 RECOMMENDATIONS

As a result of the analysis of information gathered during this investigation, it is recommended that:

1. The design of watermains for use in areas north of Lat. $45^{\circ} 30' N$ should include a more complete consideration of temperature effects than is now generally the case.

2. Flat slab insulation, while it may be made to be effective in preventing freezing conditions adjacent to a buried pipeline, should be used with caution due to possible detrimental side effects.

3. Consideration should be given to protecting water supplies against freezing by providing for continuous flow and a supplemental heat source for use if and when required.

4. If freezing protection is provided as in item 3, consideration should be given to reducing the depth of burial to less than is now generally accepted practice which, as shown, does not preclude freezing or below-freezing temperatures at the pipe depth.

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